Non- Topographic Space-Based Laser Remote Sensing

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Outline

- Introduction
- Space Laser Altimetry Instruments
- Progress on On-Going Programs
  - Earth Science
  - Planetary Science
  - Heliophysics
  - Astrophysics
- Summary

INTRODUCTION

EARTH SCIENCE APPLICATIONS

CO_2 LIDAR

CH_4 LIDAR

CARBON DIOXIDE LIDAR

NASA's ASCENDS Mission

ASCENDS

Active Sensing of CO_2 Emissions over Nights, Days, and Seasons (ASCENDS) Mission

Science Mission Definition Study

Draft

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April 15, 2015

Avail from:

http://cce.nasa.gov/ascends_2015/index.html

National Aeronautics and Space Administration | + NASA Homepage + NASA Carbon Cycle and Ecosystems

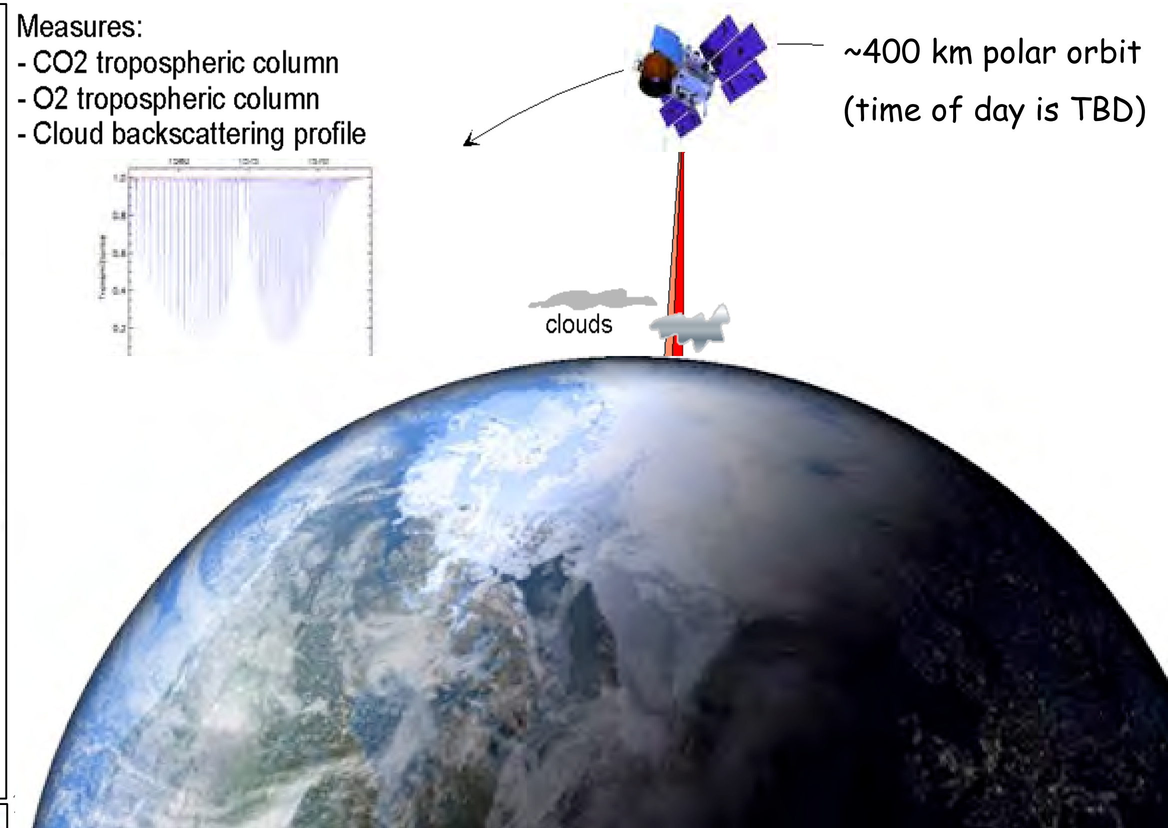
ASCENDS 2015 Workshop

Home | Agenda and Presentations | | ad hoc Science Definition Team

ASCENDS Workshop
June 19, 2015
California Institute of Technology

This workshop will be held after the *11th International Workshop on Greenhouse Gas Measurements from Space* at California Institute of Technology, Pasadena, California, USA, Friday, June 19th.

View their website for logistical information: https://sites.google.com/site/iwggms11/



Requirements for CO_2 Mixing Ratio:

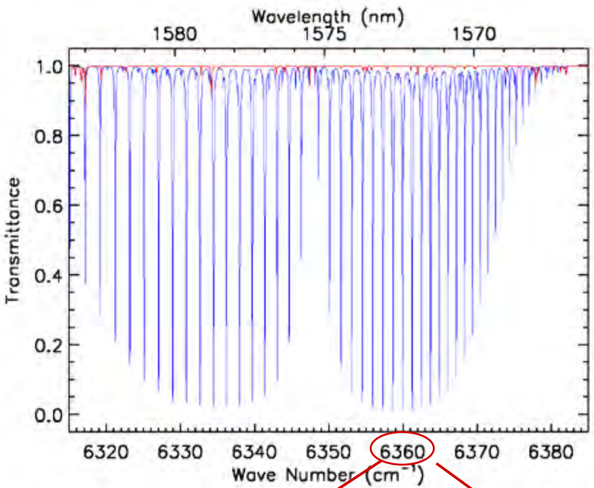
Random error**: ~ 1 ppm in ~100 km along track, or**

~ 0.5 ppm in ~10 sec over deserts

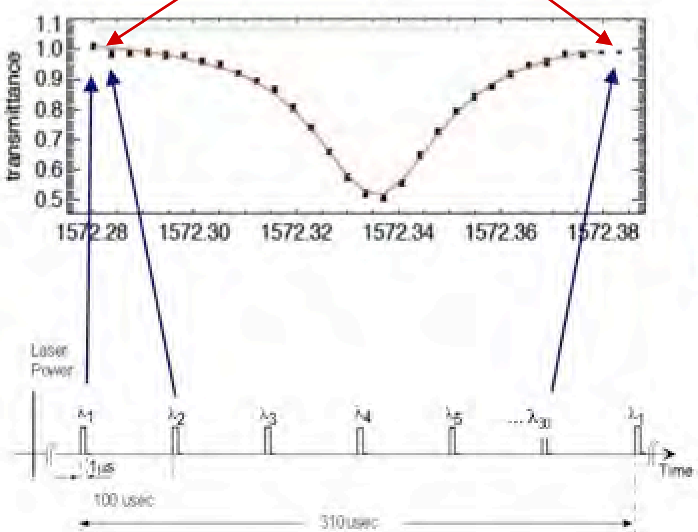
***Bias:* < 0.5 ppm (< 1 part in 800)**

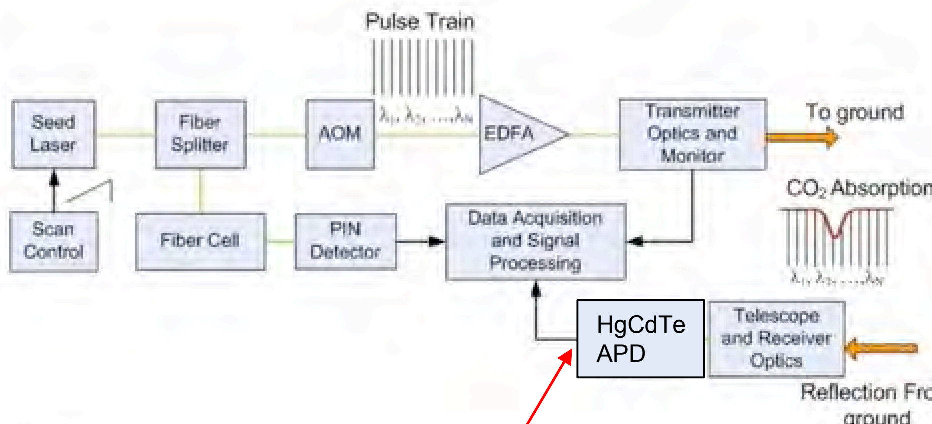
Lower errors provide more benefit for flux est's.

CO_2 Sounder Approach:
Airborne CO_2 Line Sampling & Absorption line analysis



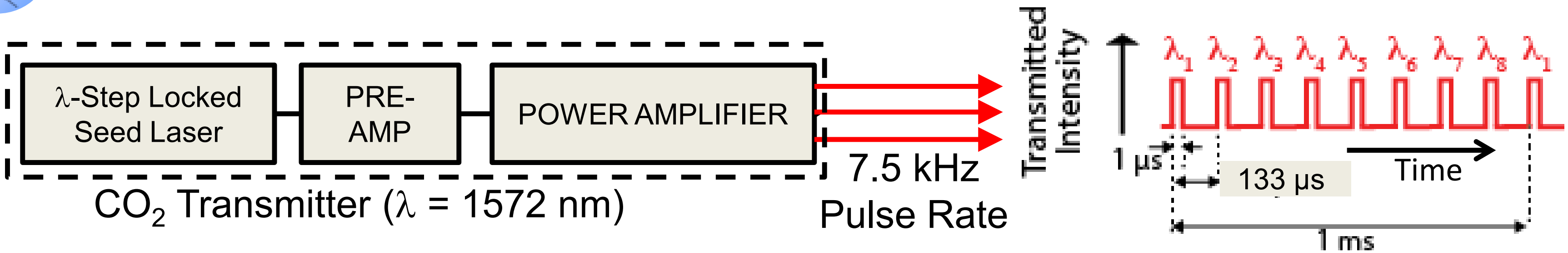
- *Line at 1572.33 nm*
- *Lidar* measures "dots" (wavelength samples) to all scattering surfaces
- *Post flight: Retrievals* (based on model atmosphere) calculates range, normalized line shapes & solves for best fit concentration

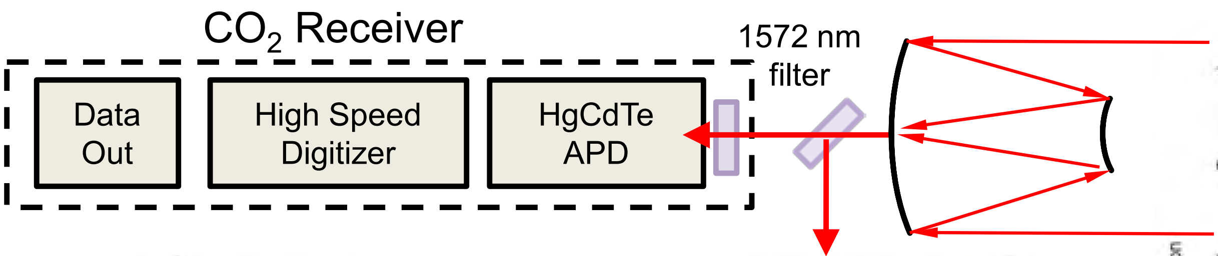


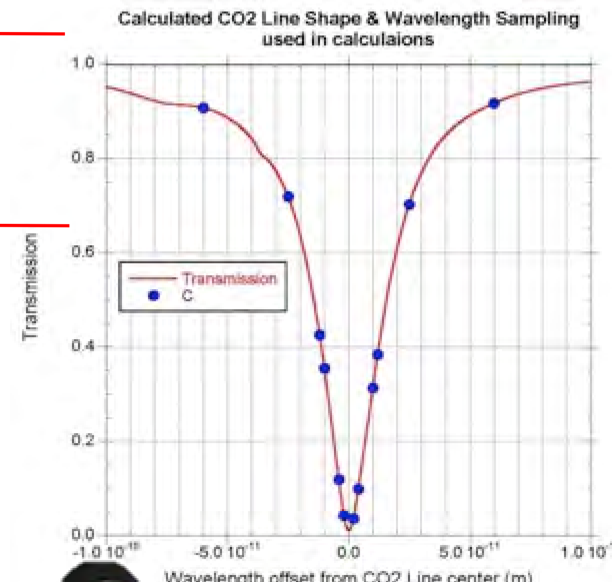


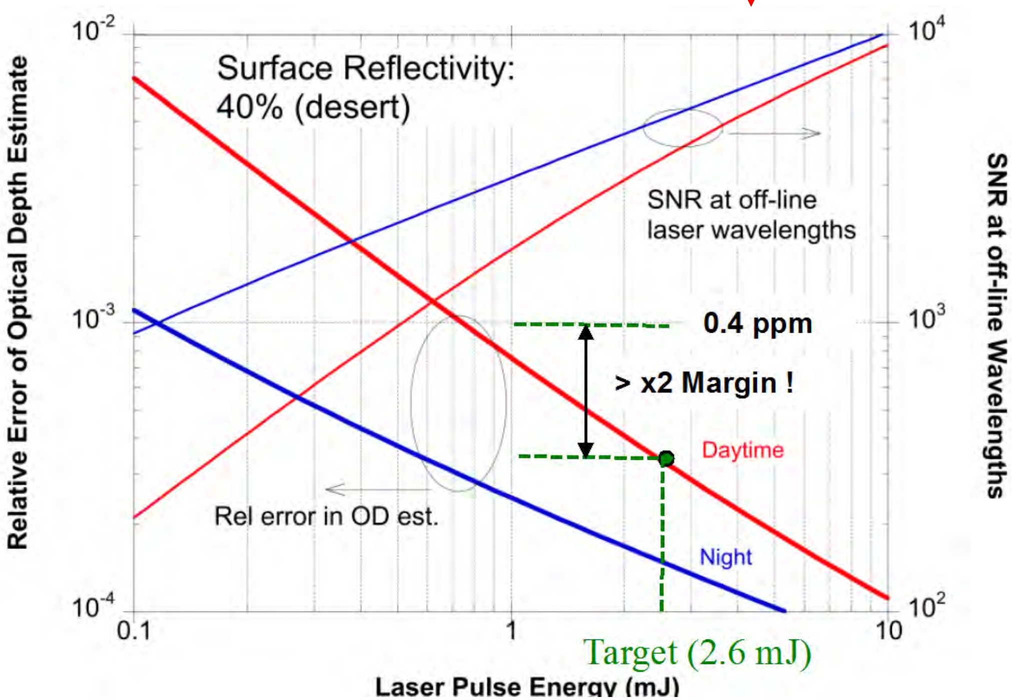
HgCdTe APD Detector in 2014 flights

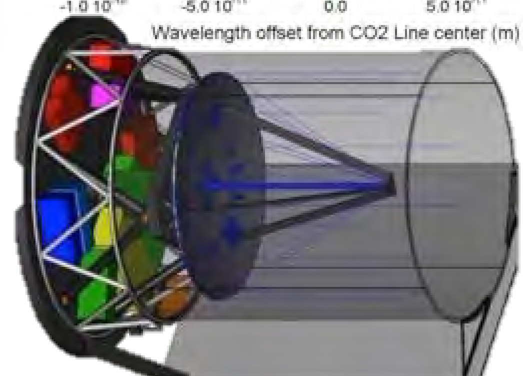
Scaling CO_2 Sounder Lidar to Space











Laser Requirements

Performance Parameter	Laser Transmitter
Center Wavelength	Nominally centered at 1572.335 nm
Linewidth (each wavelength channel)	$\leq$ 100 MHz (TBR)
Pulse repetition frequency	7.5 KHz
Pulse Width	1-1.5 μs
Pulse Energy	>3.2 mJ/pulse (goal); >2.6 mJ/pulse (operating, 18% derating)
PER [TBR]	20 dB (TBR)
Wall-plug Efficiency	> 6%

Performance Parameter	Laser Transmitter
Center Wavelength	Nominally centered at 1572.335 nm
Pulse energy stability (long term – 1 hr)	< 5%
Optical Output	Free space, PM, ~100 μrad divergence, beams co-aligned to better than ~20 μrad
Beam quality	M^2 <1.3 (TBR)
PER [TBR]	20 dB (TBR)
Environmental	Launch to ISS (TBR)
Wall-plug Efficiency	> 6%

Seed laser approach

Master laser (locked to CO_2 Absorption line) $\xrightarrow{\nu_0}$ Fast tunable slave laser (offset locked to master laser) $\xrightarrow{\nu_1, \nu_2, \dots, \nu_n}$ CW output

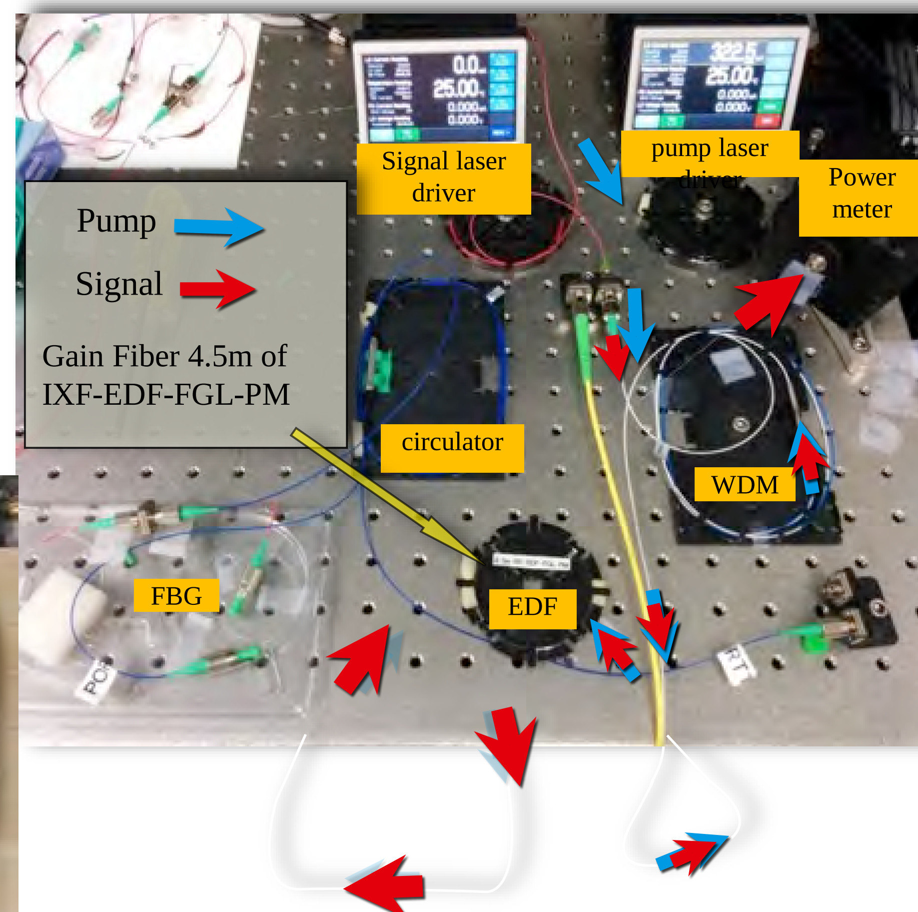
- DFB master laser is locked to CO_2 reference cell.
- Digital Supermode-DBR slave laser is dynamically offset-locked to the master DFB laser using an optical phase-locked loop (OPLL).
- Slave laser output is source for remaining laser stages.
- Frequency-stepped pulse train carved by MZM and subsequently amplified.
- Demonstrated laser frequency noise suppression (to < 0.2 MHz), tuning speed (< 40 μs) and tuning range (~32 GHz) – all satisfy or exceed ASCENDS requirements
- US Patent granted (July 2015).

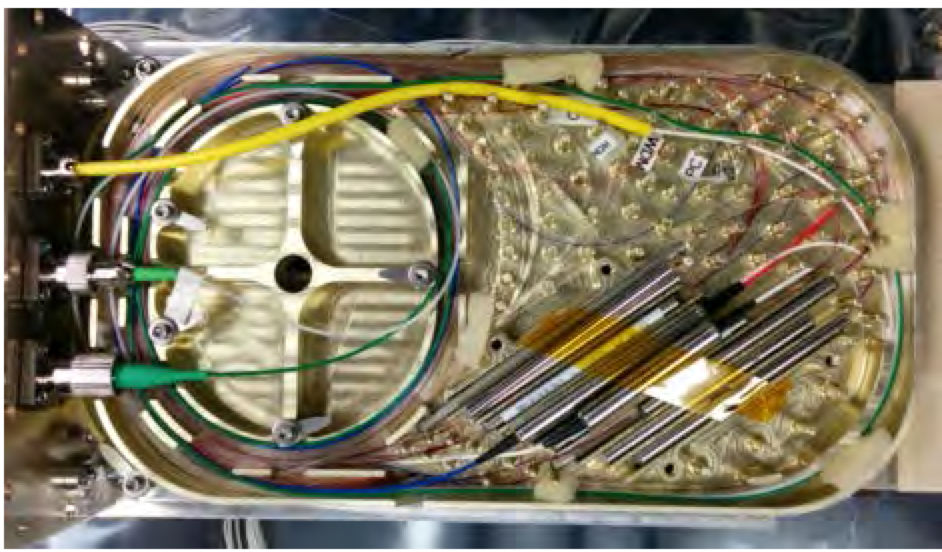
Ref: Numata, K., et al., Optics Express Vol. 20, Issue 13, pp. 14234-14243 (2012).
Numata, K., et al. Applied Optics 50.7 (2011): 1047-1056.
Chen, et al., US Patent No.: US 9,065,242 B2 (45), Jun. 23, 2015.

Pre-Amplifier Development

Preliminary Stage 1 Pre-amplifier breadboard Results

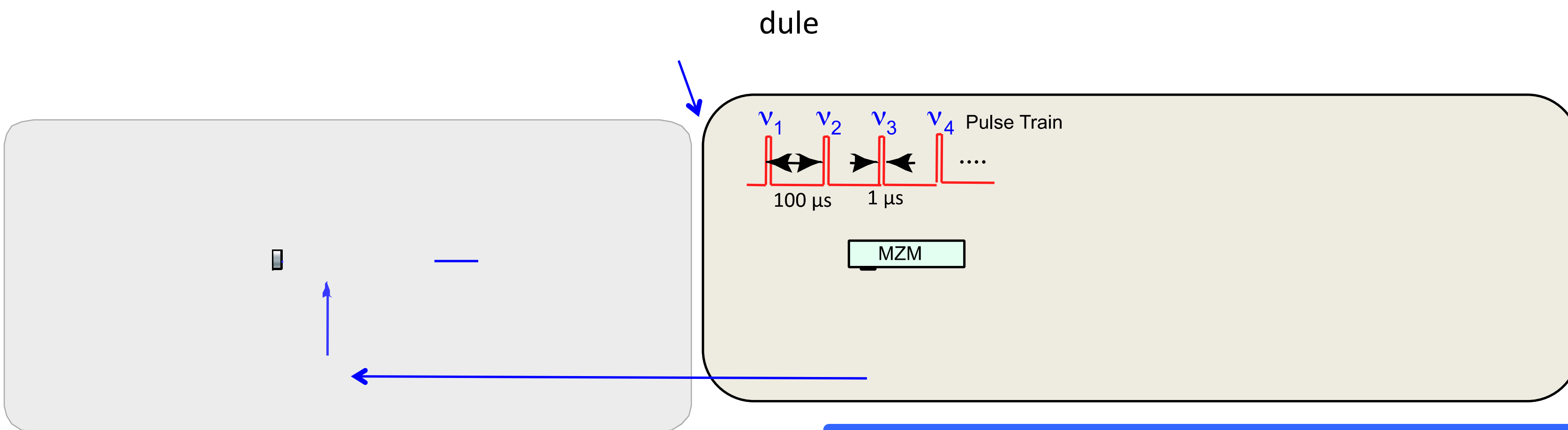
- 4.5 meter IXF-EDF-FGL-PM
- Core pumped
- Pump power 200mW @ 976 nm
- Input 9mW of 1572.3nm
- Measured Output ~80mW
- Measured Gain ~10dB
- ASE filtered with FBG



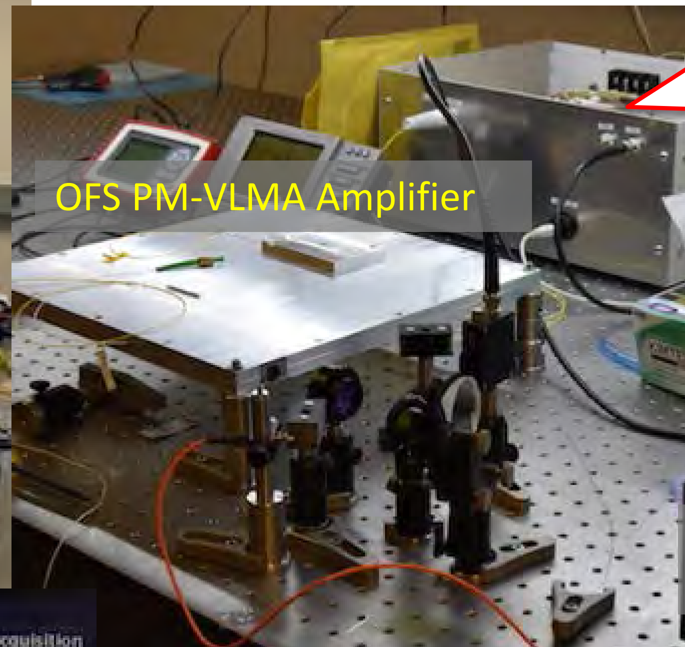


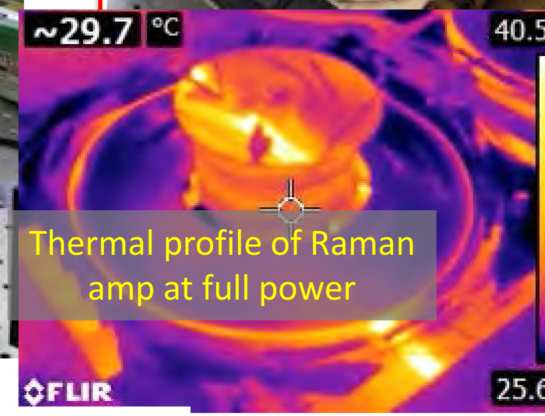
Packaging Approach

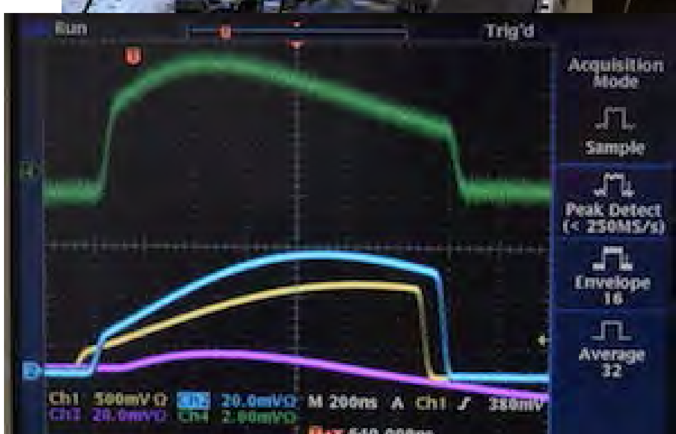
Power Amplifier



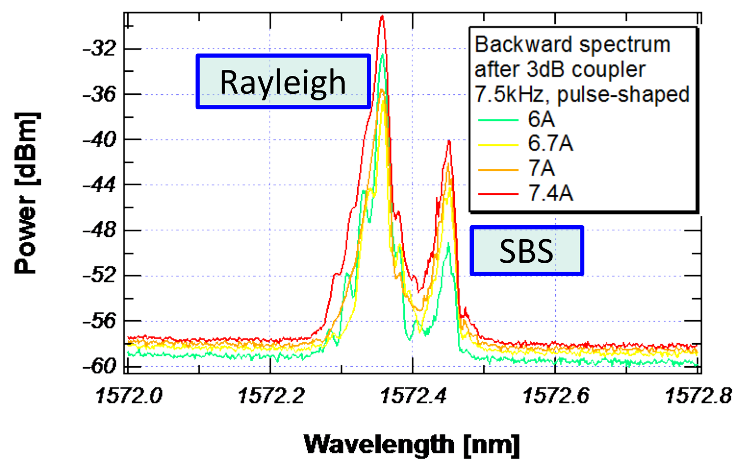
OFS PM-VLMA Power Amplifier Performance







Pre-shaped pulses from seed (yellow) and preamplifier (blue) and VLMA Output Pulse shape (Green); Red is ASE from VLMA



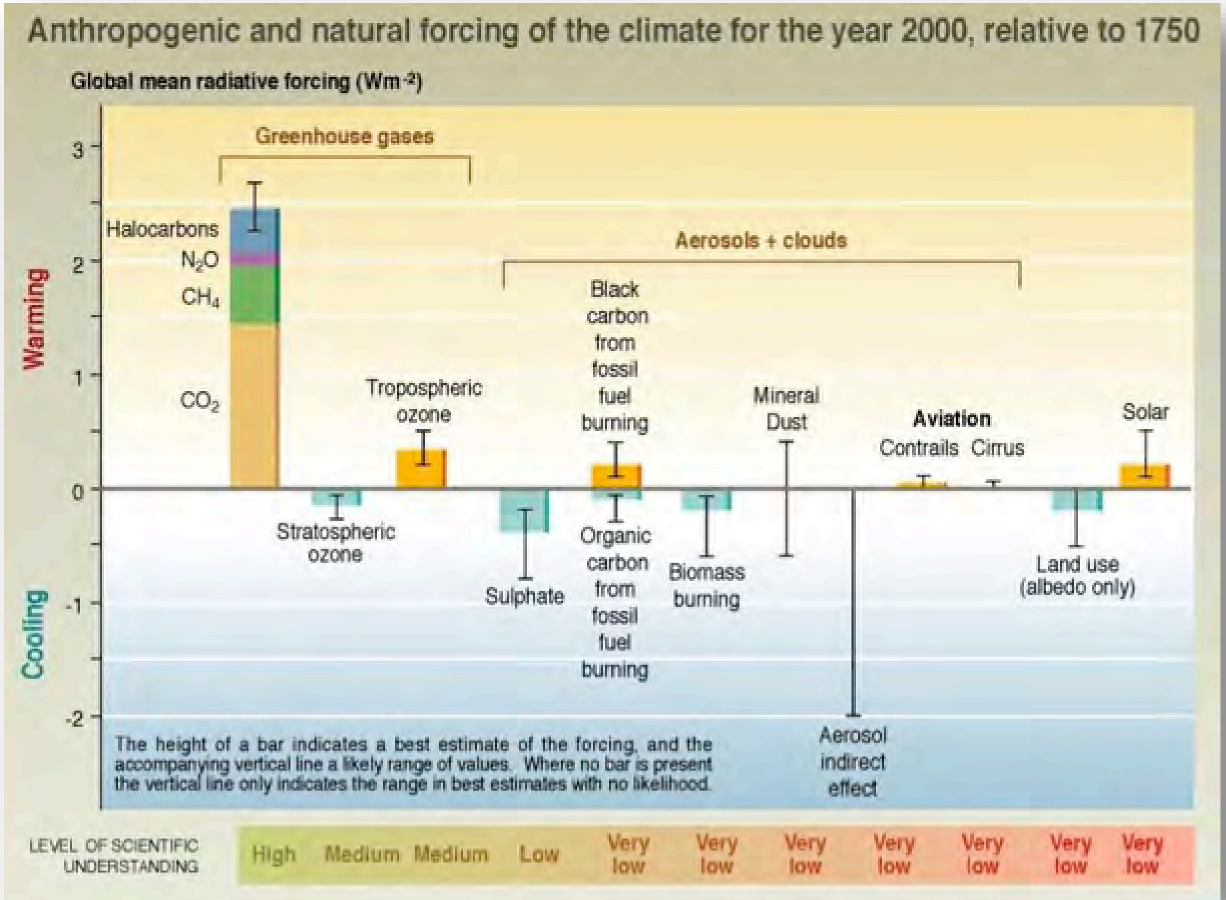
Breadboard Performance (w/o optimized pre-shape pulse –

460 µJ at 7.5 kHz, 1 µs pulse

6X would provide ~2.8 mJ

METHANE LIDAR

Methane radiative forcing

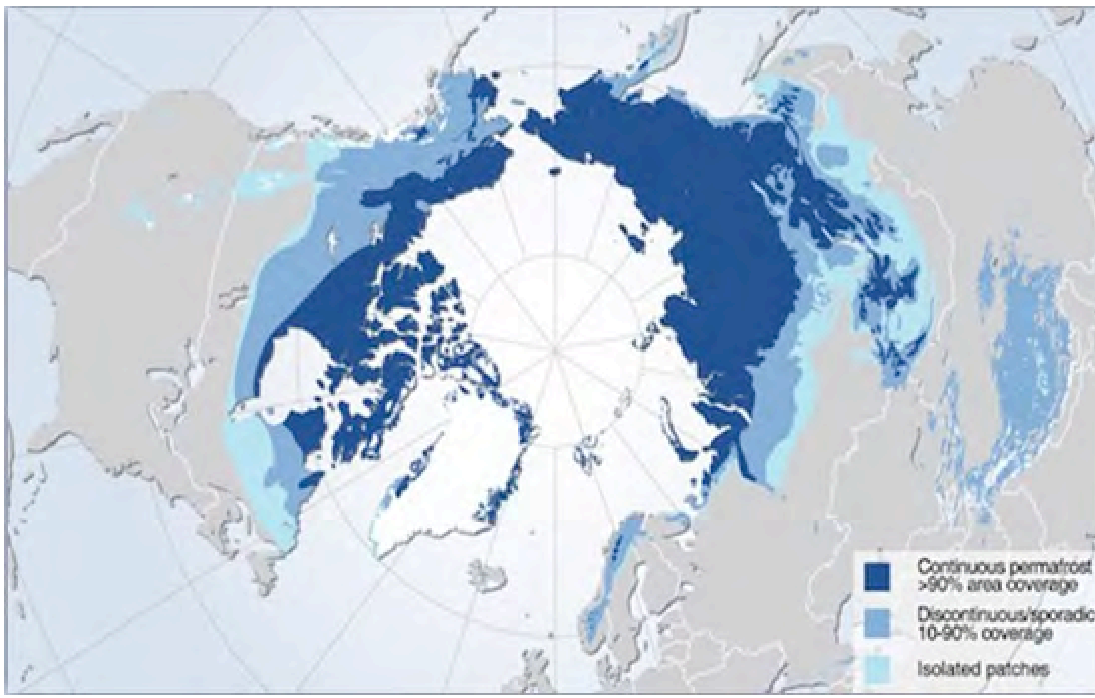


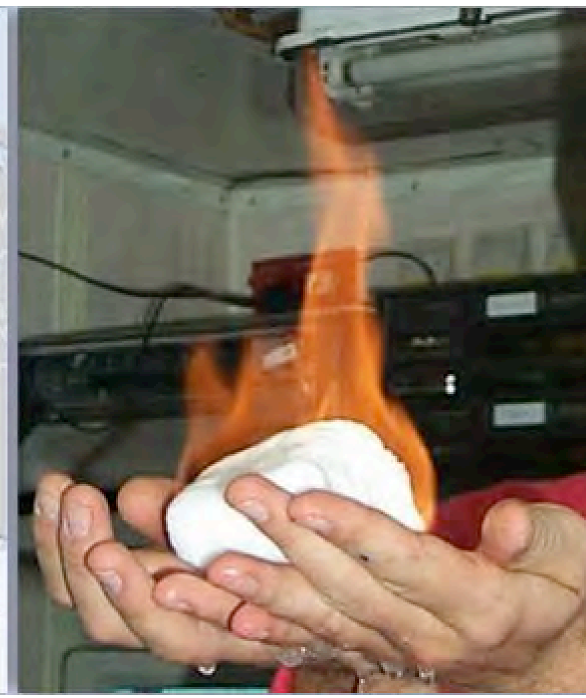
Source: IPCC Report 2007

- CH_4 is a strong greenhouse gas (~×23-25 higher radiative forcing than CO_2 on a per molecule basis).
- <u>Earth Science Decadal Survey (NRC 2007):</u>
  - *"Ideally, to close the carbon budget, methane should also be addressed, but the required technology is not now obvious.* ***If appropriate and cost-effective methane technology becomes available, methane capability should be added."***

Methane "Arctic Time Bomb"

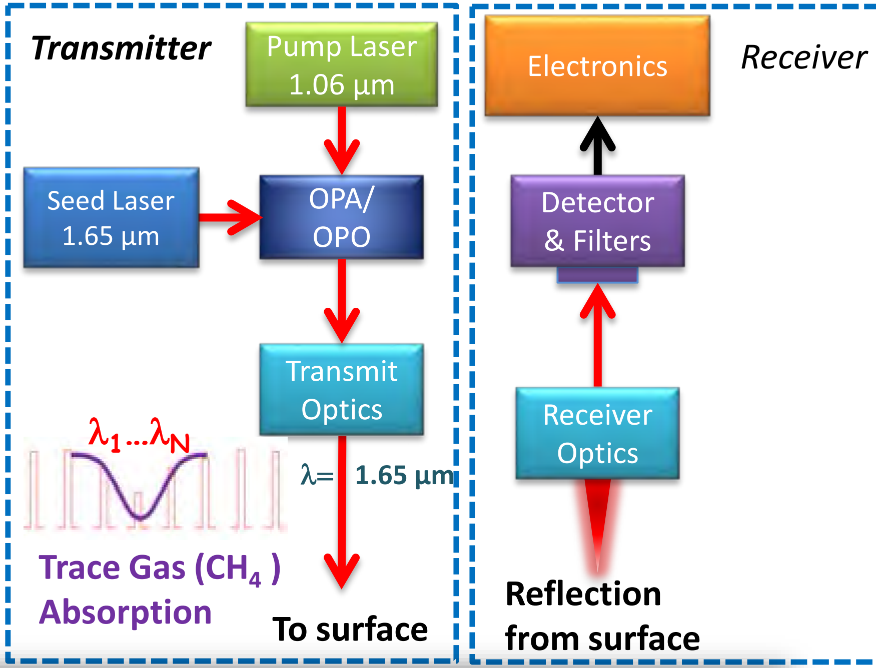
- Increasing concern about CH_4 in the Arctic: ***"Is a Sleeping Climate Giant Stirring in the Arctic?".*** *Large amounts of organic carbon are stored as CH_4 and CO_2 in the Arctic permafrost. Thawing Arctic permafrost soil, is a cause for concern as a rapid, positive greenhouse gas/climate feedback. In addition, large but uncertain amounts of CH_4 are sequestered as gas hydrates in shallow oceans and permafrost soils, which are also subject to potential rapid release.*

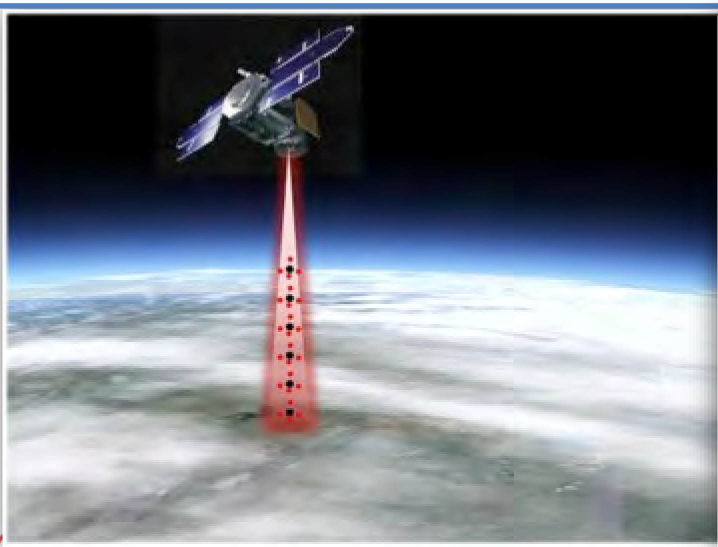


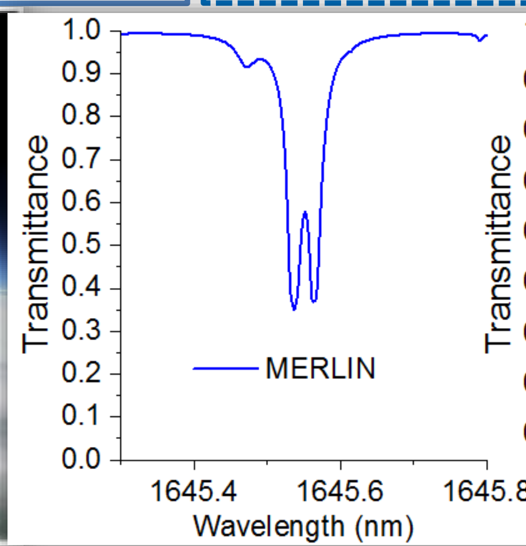


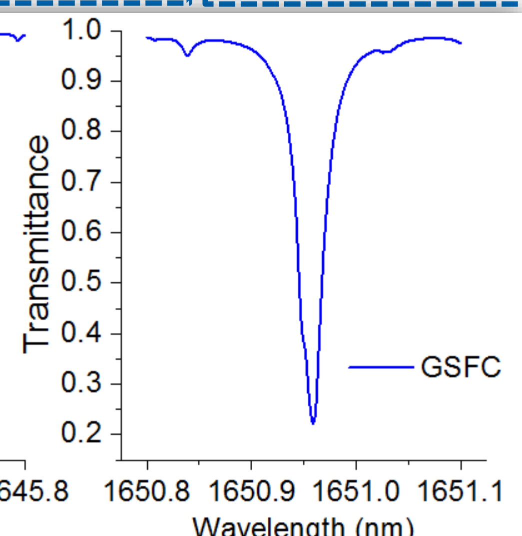
CH_4 Detection with Lidar

- ***<u>Transmitter (Laser) technology</u>***
  - ➢ **Current (optimum) Wavelength for CH_4 Earth Detection: ~1.64-1.66 µm**
  - ➢ **Optical Parametric Oscillators (OPO) and Optical Parametric Amplifiers (OPA) are the best solutions currently available for a transmitter.**
  - ➢ **Other options (Er:YAG and Er:YGG) also possible**
- ***<u>Receiver (Detector) Technology</u>***
  - ➢ **DRS e-APD**









Methane Transmitter Components

Pump: a high power, single frequency, narrow linewidth fiber or solid state laser at ~1064 nm or 1030 nm

ν_1 **Pump**

ν_2 (t) Seed(s)

OPO/OPA

ν_1 Residual Pump-not used

ν_3 Idler-not used

ν_2 (t) Signal (1651 nm)

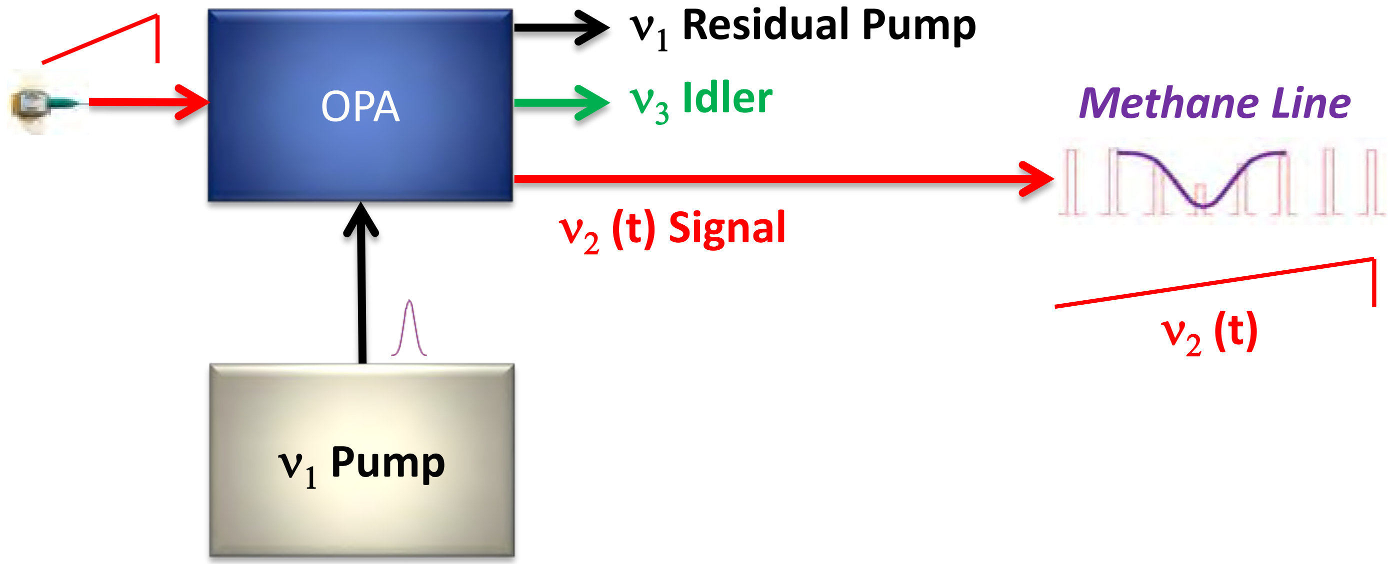
Methane Line

Seed: a (low) power, single frequency diode laser at 1651 nm.

Optical Parametric Oscillator (OPO) or Optical Parametric Amplifier (OPA).
A non-linear crystal that amplifies the seed laser to the energy needed for space ***without*** degrading the spectral characteristics

All components are critical and require technology development

Transmitter Technology - OPA



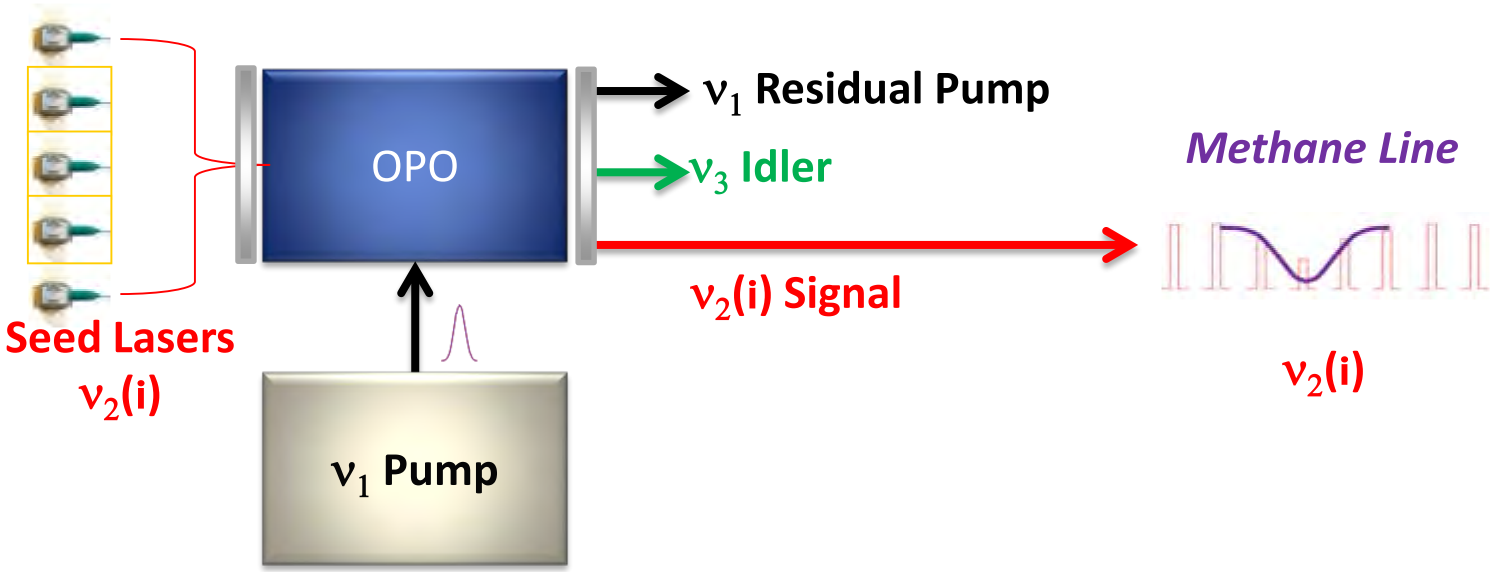
OPA: OPA samples the CH_4 line at several wavelengths using a <u>single,</u> <u>continuously tuned</u> seed laser.

Easy to align, easy to tune, hard to achieve power scaling <u>while maintaining narrow linewidth</u>.

Need to increase seed laser power.

Burst mode pump laser an alternative approach.

Transmitter Technology - OPO



- *OPO samples the CH_4 line at <u>several discrete wavelengths using multiple seed lasers</u>.*
- *Complicated to align and tune; power scaling easier to achieve while maintaining narrow linewidth.*
- *Master laser locked to the CH4 absorption*
- *Cavity locked to master laser*
- *Remaining seed lasers offset-locked by integral number of cavity modes*

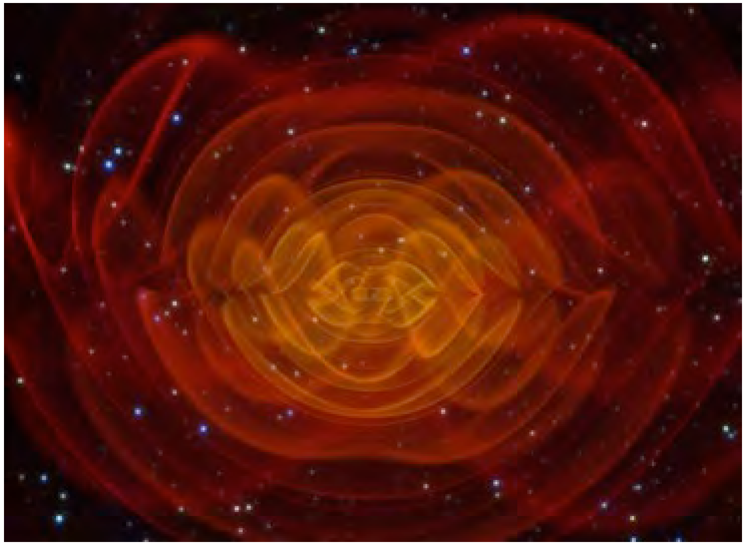
Summary

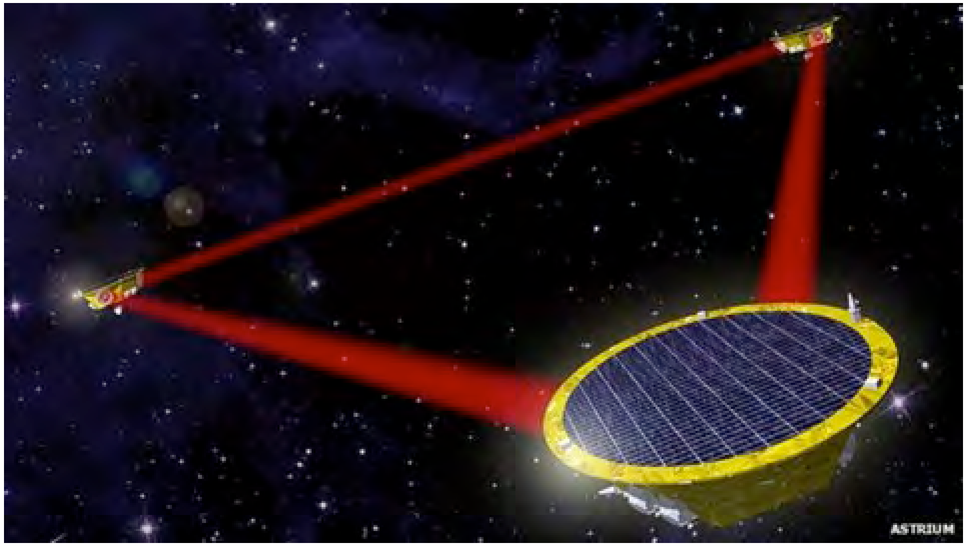
- Methane measurements are needed over all latitudes and seasons.
- Airborne demonstration with DRS detector and two candidate architectures for a CH_4 transmitter: 20-wavelength OPA and 5-wavelength OPO.
  - DRS detector worked well during flight. Its performance is close to CO_2 (as expected).
  - Both OPA and OPO performance was better than expected during flight.
    - 20 wavelength OPA gave better results (precision) but there is no simple path to scale the power of the transmitter to space.
    - 5 wavelength OPO gave good results (when detector was not saturated). Can use more wavelengths but is already close to the energy we need for space.
- Transmitter Plan - Many different approaches and options for laser transmitter were investigated.
  - Er:YGG/Er:YAG (<u>Baseline</u>)
  - OPO (<u>Backup</u>):
  - Burst Mode OPA (no easy path to space)
  - Single Pulse OPA (no easy path to space)
- **Plan will provide at least one baseline configuration (Er:YGG) and at least one backup configuration (OPO) that can be flown.**
- Leveraged SBIR, IRAD, and Tipping Point programs.
- Significant progress has been made with modest investments.

ASTROPHYSICS

Science of Gravitational Waves/eLISA

- eLISA (evolved Laser Interferometer Space Antenna)
  - Planned late 2020s ~ early 2030s launch
  - https://www.elisascience.org
- New way to observe the universe
  - Expected astrophysical GW sources in eLISA
    - Black holes and galaxy formation
    - Merging massive black holes in galaxies at all distances
    - Massive black holes swallowing smaller compact objects



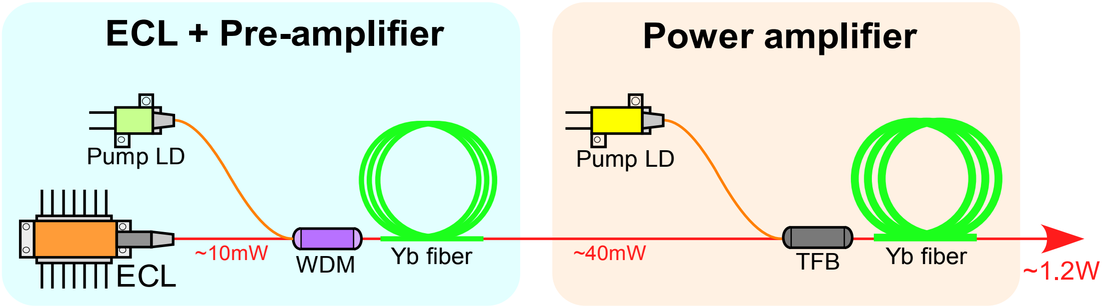


eLISA laser requirement

- Unique requirements for precision interferometry
  - Continuous-wave laser
  - Single-mode & frequency
  - Extreme stability in frequency & intensity

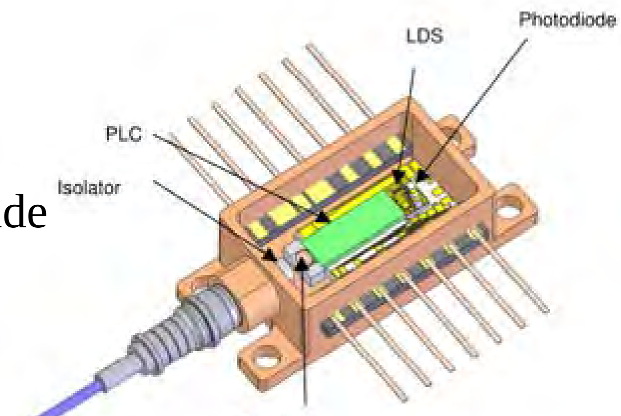
Power	λ (nm)	Intensity noise ($/Hz^{1/2}$)	Frequency noise ($Hz/Hz^{1/2}$)	Differential phase noise ($rad/Hz^{1/2}$)	Lifetime
1.5 W	1064	10^{-4} (@ 10^{-3} Hz) 10^{-8} (@ 10^{7} Hz)	300 (@ 10^{-2} Hz)	6×10^{-4} (@ 10^{-2} Hz)	2.5 years

- eLISA laser configuration
  - All-fiber master oscillator power amplifier (MOPA)

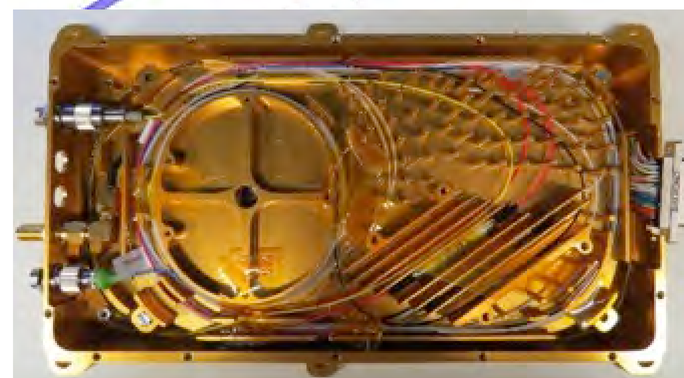


Current Activities & Future Work

- Master oscillator
  - Working with RIO to build low noise planar-waveguide ECL
  - Environmental test to be completed soon at RIO
  - On-chip phase modulator planned



- Pre-amplifier
  - ~150mW CW output
  - Prototype was built, packaged, and tested
  - Environmental testing being done

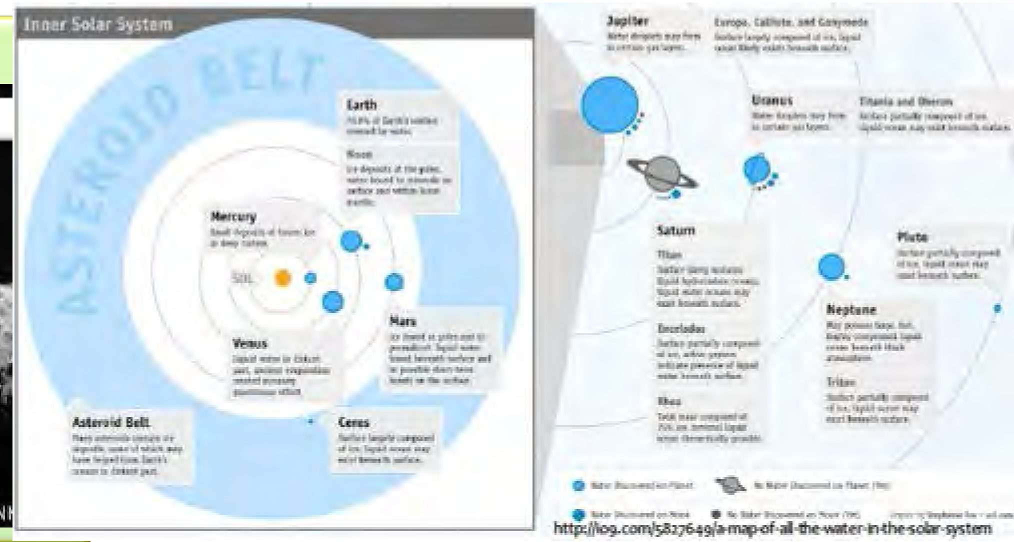


- Power amplifier
  - All-fiber design, ~2.4W CW output
  - Noise measurement & stabilization being done
  - Full laser system noise & reliability tests planned

PLANETARY SCIENCE

TIME OF FLIGHT MASS SPECTROMETER

Science Motivation



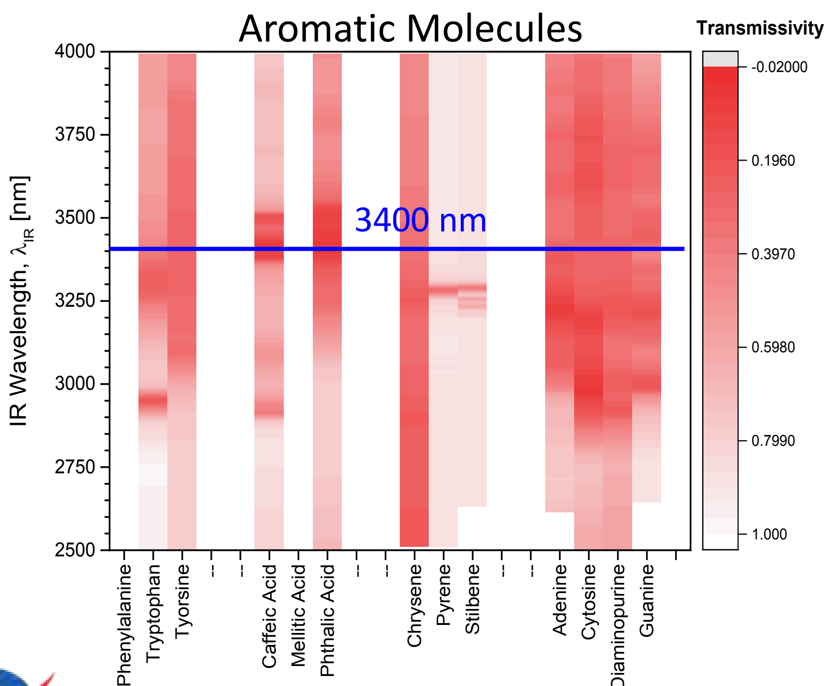
All these bodies contain volatiles, including water just waiting to be analyzed

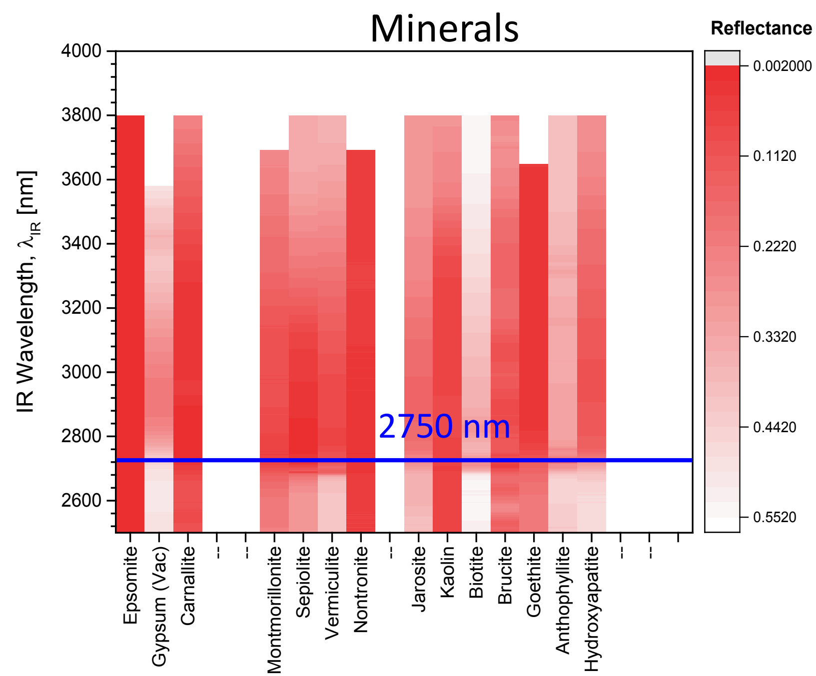
Our science motivation is to seek a solution with "Universal" detector for

- Comprehensive sample analysis
- Flexibility to adapt for different mission architectures including flybys, orbiters, landers, and/or rovers!

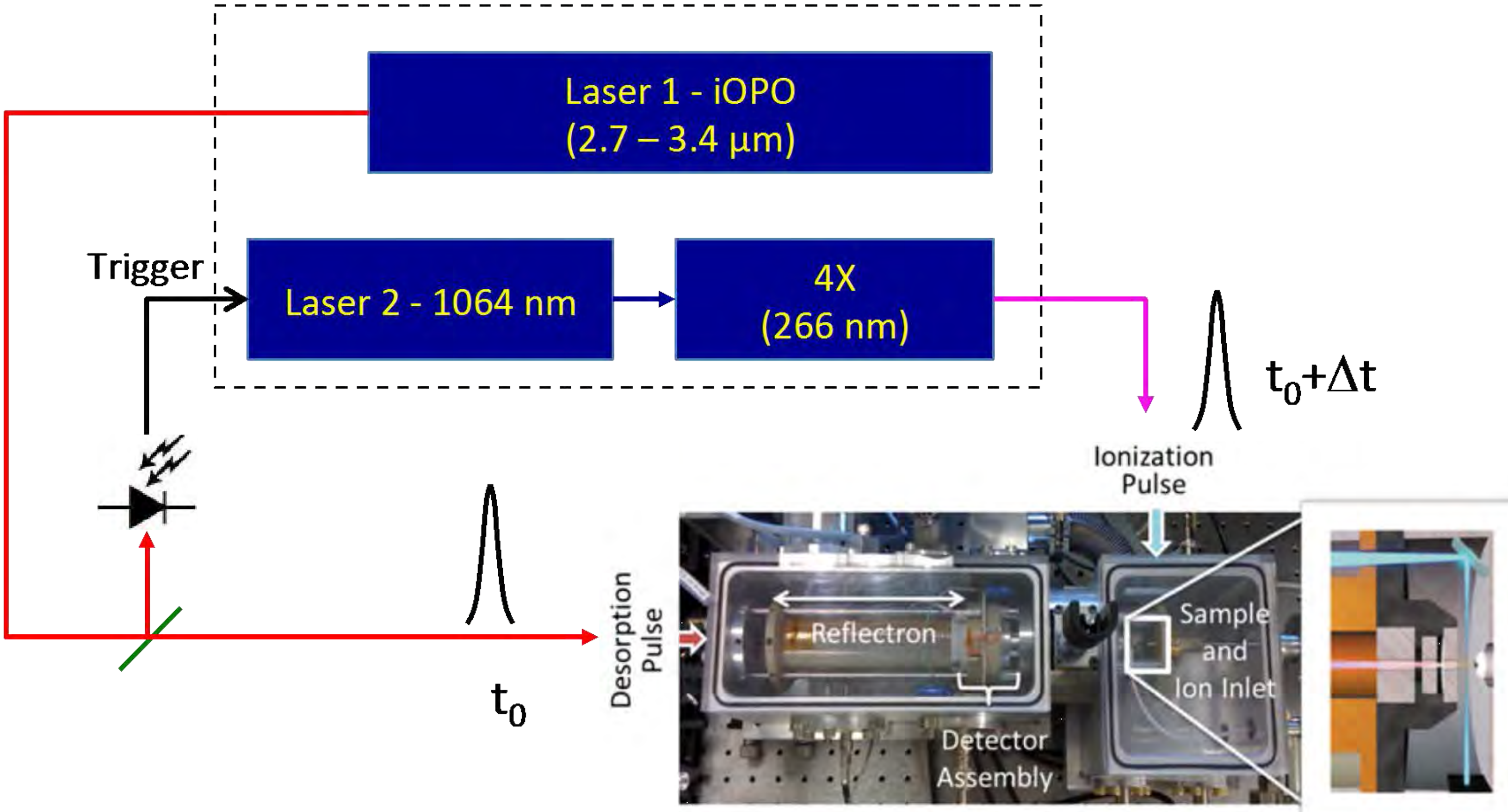
L2MS Instrument Overview

- Wavelengths are selected based on key vibrational and electronic resonances in the targeted species aligned with the organic diversity and mineralogy expected for future planetary missions of high priority to NASA
  - 2.75 µm - IR vibrational resonances of hydrated minerals
  - 3.4 µm - C-H vibration resonance of organic species
  - 266 nm - coincides with a short-lived metastable state in many aromatic molecules
- Matching MIR laser wavelength allows for selective desorption





L2MS Instrument Overview



- Typical delay between Laser 1 and Laser 2 (Δt) range between 0.3-2 µs

L2MS Laser Requirements

Lasers Requirement	MIR Laser	UV Laser
Pulse Repetition Frequency (PRF)	1 – 20 Hz	1 – 20 Hz
Wavelength	2.8X µm and 3.40±0.05 µm	266 nm
Energy	~ 100 µJ	~ 18 µJ
Pulse Width	< 7 ns	< 7 ns
Peak Power	~14 kW	~2.5 kW
Peak Intensity (assuming 100 µm beam diameter)	180 MW/cm^2	~30 MW/cm^2
Spectral Width	Few GHz	Few GHz
Timing	t_0	$t_o + \Delta t$; ~100 ns < Δt < few µs
Laser Lifetime	3 year mission at 10% duty cycle ~ 64 Mshots @ 20 Hz	

Future Work

Laser 1 – MIR Laser

- Test 3.4 µm breadboard with L2MS laboratory instrument and compare with commercial OPO
- Complete 2.75 µm breadboard laser
- Finalize design for dual wavelength (2.75 µm and 3.4 µm) concept

Laser 2 – UV Laser

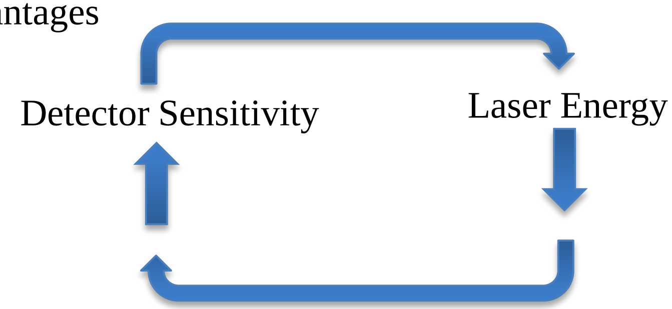
- Investigate other non-linear optical crystals for SHG and FHG – leverage ICESat-2/ATLAS LBO aging study
- Optimize overall 4th harmonic conversion efficiency
- Test breadboard with L2MS laboratory instrument and compare with commercial UV laser
- Develop epoxy-free opto-mechanical design for mounting optics to minimize UV induced contamination on optical surfaces

Laser Transmitter

- Improve packaging of the laser transmitter for space flight
- Build brass board laser transmitter that will generate both MIR and UV wavelengths on a single laser bench

Preparing for the Future

- Use nonlinear optical processes to generate specific wavelengths for laser spectroscopy
- New approaches in laser architectures
  - High rep rate, lower pulse energy, sub-ns pulse for high resolution mapping (8-10 kHz, >50 μJ, <2 ns)
  - High efficiency laser systems (>15% wall plug)
  - Highly reliable laser systems (multi-Billion shots)
  - High sensitivity detector and detector arrays with low-noise, high speed ROICs
    - linear mode PC in the NIR because of its wavelength advantages
  - Data volume management
    - On-board data processing
    - Data compression
    - High data downlink rate



- Common requirements for all laser based instruments
  - Lifetime
  - Reliability
  - Efficiency